REEVALUATING GROOVE FORMATION ON GANYMEDE: FORMING LARGER-AMPLITUDE GROOVES AT SMALLER EXTENSIONAL STRAINS.

M. T. Bland and W. B. McKinnon, Department of Earth and Planetary Science, and McDonnell Center for Space Sciences, Washington University in Saint Louis, MO 63130. (mbland@levee.wustl.edu).

Overview: Much of Ganymede's surface consists of sets of periodic, sub-parallel ridges and troughs with peak-to-trough amplitudes of several hundred meters. Recent numerical modeling has confirmed that groove-like structures result from the extension of an ice lithosphere [1,2]. However, these models require large-strains (20-30%) to produce groove-like amplitudes, and suffered from unrealistically large element dilation during brittle deformation (a by-product of so-called associated plasticity). Here we show that implementation of more realistic brittle rheologies (i.e., non-associated plasticity) and strain weakening results in groove-like deformation amplitudes at moderate strains (~10%) without excessive element dilation. The smaller required strains are more consistent with Ganymede's global strain inventory.

Ganymede's Grooved Terrain: Ganymede's grooved terrain (~2 Ga) covers roughly two-thirds of the surface. The terrain consists of sets of roughly parallel, periodically spaced ridges and troughs [see 3 for a comprehensive review]. Ridge sets are typically tens of kilometers wide and hundreds of kilometers long. Groove amplitudes and wavelengths are typically several hundred meters and 3-10 km, respectively [4,5].

Current consensus suggests that Ganymede's grooves formed during extension of the lithosphere via periodic necking instabilities. In this model large-amplitude grooves result from periodic pinch-and-swell structures (analogous to boudinage), which are accommodated by smaller-scale tilt-block faulting (consistent with the smaller-scale deformation observed at high resolution) [3,6].

This conceptual model has been supported by both semi-analytic [7] and numerical models [1,2]. However, several questions remain unresolved. Recent numerical models require large lithospheric extension (20-30%) before groove-like amplitudes are reached. Large extensional strains have been inferred on Ganymede [8]; however, such large strains may not be typical of groove terrain in general, and appear inconsistent with Ganymede's global strain balance [9]. Here we describe a new model of groove formation that requires smaller extensional strain to produce large-amplitude grooves, and we provide a preliminary evaluate.

Simulating Groove Formation: We use the finite element model Tekton2.3 to simulation groove formation. The viscoelastic-plastic model has been described extensively in [1,2]. Here we assume a pure water ice rheology with a grain size of 1 mm. The surface is initialized with random, low-amplitude topography. The model includes a strain localization mechanism [see 2] and now implements non-associated plasticity to control element bulking [10].

Non-Associated Plasticity: Plasticity is a continuum approach to modeling the accumulated strain resulting from small-scale (i.e., sub-element) brittle deformation. Plasticity can be "associated," wherein the plastic strain rate is a specifc function of the yield criterion (strains are prependicaular to the yield surface), or "non-associated," wherein the strain rate is a function of a more general plastic potential. Associated plasticity is simpler to implement numerically, but results in unrealistic element dilation (bulking) as plastic strains become large. Bulking can be minimized or eliminated by using non-associated plasticity (note that modest bulking – gauge formation – is expected for realistic materials undergoing brittle failure). We use the plastic potential

$$g = J_2^{1/2} - I_1/3 \sin\varphi,$$

where J_2 is the second invariant of the deviatoric stress, I_1 is the first stress invariant, and φ is the dilation angle. Small dilation angles result in small element dilation. We utilize values between 5°-10°.

Model Results: The surface deformation and the distribution of plastic strain in the lithosphere is shown after 10% extension in Fig. 1 for a simulation with a thermal gradient of 20 K km^{-1}, strain rate of 10^{-13} s^{-1}, and plastic dilation angle of 5°. Extension has resulted in periodically spaced graben-like troughs separated by relative undeformed regions. Maximum peak-to-trough amplitudes have reached >400 m, with average amplitudes of ~300 m. Groove wavelengths are ~10 km. Both the amplitude and wavelength is consistent with observations of archetypical grooves on Ganymede.

Figure 2 expands a portion of the simulated lithosphere (and surface) shown in Fig. 1. While the magnitude of the plastic deformation is high throughout the deformed region, the majority of the deformation occurs along two linear, antithetic fault-like structures, a pattern strongly resembling that expected for a graben. Notably, the antithetic fault-like structures intersect not at the brittle ductile transition but at a shallower depth [see 11].

Despite the morphological similarities to graben, the strong periodicity of the deformation (the initial topography was non-periodic) and the decrease in lithospheric thickness beneath the troughs (i.e., pinching) indicates that the overall form of the deformation is controlled by viscous necking of the lithosphere.

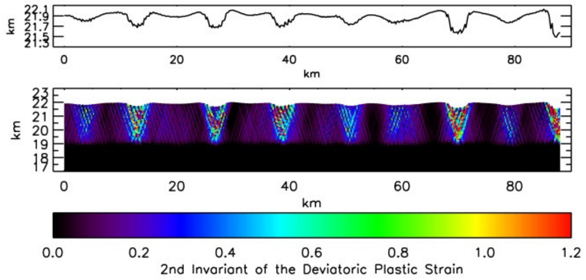

Figure 1: Profile of the surface deformation (top) and color map (length and depth) of the plastic strain distribution throughout the lithosphere (after 10% extension). Only the top five kilometers of the model domain are shown.

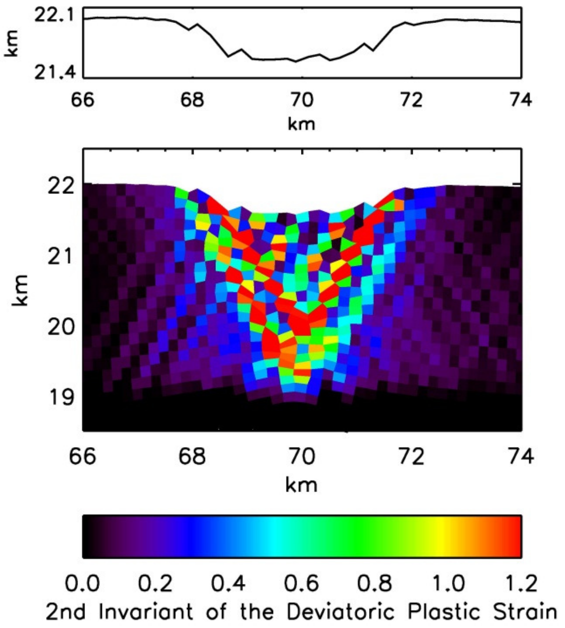

Figure 2: A portion of the lithosphere and surface shown in Fig. 1. Vertical exaggeration is close to zero. Note the antithetic fault-like structures (regions of high plastic strain) bounding the trough.

Non-Associated Plasticity vs. Strain Weakening: Figure 3 shows a simulation identical to that in Fig 1 but without strain weakening. Groove amplitudes in Fig. 3 average ~200 m with a maximum of ~300 m. These magnitudes are only modestly lower than those in Fig. 1. Notably, the amplitudes are also comparable to those achieved by previous models *with* strain weakening, but with *associated* plasticity (and at larger strains) [2]. Switch from associated to non-associated plasticity dramatically increases deformation amplitudes, likely by surpressing unrealisticly large element dilation that "filled in" groove troughs.

The deformation in Fig. 3 lacks the fault-like structures shown in Fig. 2, which result directly from the strain localization mechanism. The more distributed strain pattern results in undulatory ridges and troughs, rather than graben-like features. Both morphological types are observed on Ganymede [6], and their occurrence may depend on the local weakening behavior of the lithosphere (as previously suggested by [2]).

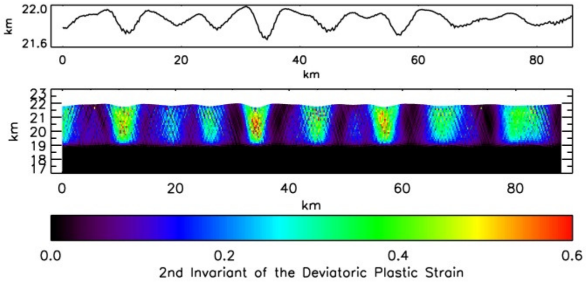

Figure 3: As in Fig. 1, but for a simulation without strain weakening. Note the change in color scale.

Summary and Continuing Work: Here we show that groove-like structures result from ~10% extension of the lithosphere when realistic non-associated plasticity is used (with or without strain localization). The extensional strain required is a factor of two less than in previous models, and is more consistent with Ganymede's global strain balance. Strain weakening affects the morphology, and increases the amplitude, of the deformation. We are investigating alternative localization prescriptions that more realistically encapsulate the observed weakening of geologic materials (e.g., loss of cohesion and a decreased, but finite, friction angle). However, these weakening mechanism will likely affect the detailed morphology of the surface deformation, more than groove amplitudes.

Acknowledgment: Supported by OPR and PGG.

References: [1] Bland, M. T. and Showman, A. P. (2007) *Icarus 189,* 439-456. [2] Bland, M. T. et al. (2010) *Icarus 210,* 396-410. [3] Pappalardo, R. T., et al. (2004) in *Jupiter: The Planet, Satellites, and Magnetosphere*, Cambridge. [4] Squyres, S. W. (1981) *Icarus 46,* 156-168. [5] Giese, B. et al. (1998) *Icarus 135*, 303-316. [6] Pappalardo et al. (1998) *Icarus 135,* 276-302. [7] Dombard, A. J. and McKinnon, W. B. (2001) *Icarus 154,* 321-336. [8] Pappalardo, R. T. and Collins, G. C. (2005) *J. Struct. Geo. 27*, 827-838. [9] Collins, G. C. (2006) *LPSC XXXVII,* 2077. [10] Bland M. T. and McKinnon W. B. (2011) *LPSC 42,* 2482. [11] Singer et al. (2013) *LPSC 44,* this meeting.